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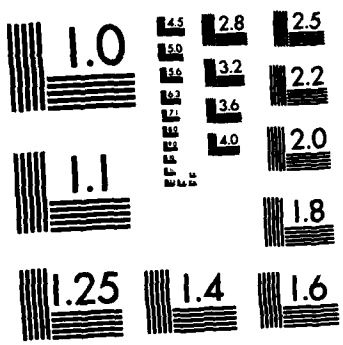

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STRUCTURE AND CHARACTERISTICS OF HETEROGENEOUS DETONATION

Final Report

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September 1983

U.S. Army Research Office

Contract No. DAAG 29-80-K-0040

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This report represents a final report covering a three-year effort on ARO Contract No. DAAG 29-80-K-0040. The technical results obtained are briefly presented and discussed and sections are included which enumerate publications, scientific personnel associated with the program, and degrees earned by students while active on this research project.

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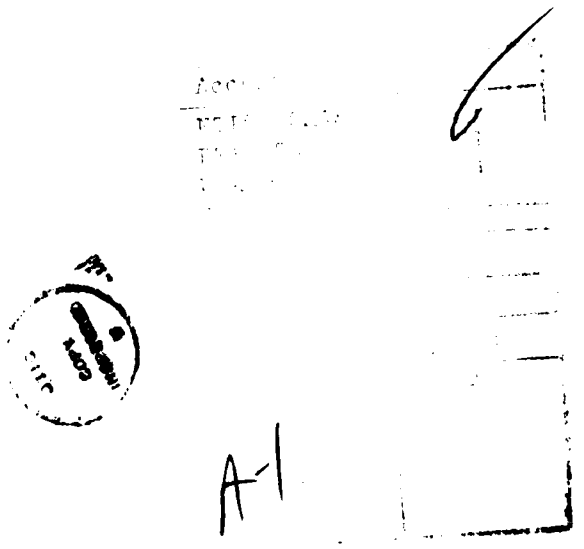
The emphasis of this research program centered around the structure of heterogeneous detonation waves, inasmuch as this had been found to be very important to the detonation characteristics of heterogeneous mixtures. On the experimental side, a vertical detonation tube was used wherein liquid fuel drops, all of one size, were generated at the top of the tube and allowed to fall vertically into the desired gaseous mixture. A strong blast wave was transmitted into the mixture through use of an auxiliary shock tube. The propagation of the resultant wave was monitored by pressure switches, pressure transducers, and photography. The low vapor pressure liquid fuel, decane (400 ~~μm~~ drop size) was used for most of the experiments. Attention was given to wave structure, wave velocity, and initiation energy. Three atmospheres (100% O_2; 40% O_2/60% N_2; and air) and a number of equivalence ratios were investigated. Holographic pictures and streak photography were employed to study the drop shattering process and the structure of the front. Other experiments investigated the addition of the sensitizer, normal propyl nitrate (NPN), to the decane. The important aspect of vapor pressure was studied by heating the entire tube to various elevated temperatures and then noting the effect on detonability.

On the analytical side, a numerical code was employed to predict the developing structure of the blast initiated heterogeneous wave. A model, based on energy, was developed for the induction zone length which could then be used in a simplified theory. The two-phase flow equations for the induction zone of the detonation, prior to the onset of combustion, were set up and integrated numerically.

FOREWORD

The research described herein was conducted under Contract No. DAAG-29-80-K-0040 over the period 1 July 1980 until 1 July 1983 at the Gas Dynamics Laboratories, Department of Aerospace Engineering, The University of Michigan. Professors J. A. Nicholls and M. Sichel served as Co-Principal Investigators. The Army Research Office Scientific Program Officer was originally Dr. Robert E. Singleton and, later, Dr. David M. Mann. Dr. Norman Slagg, ARRADCOM, Dover, N.J., was the Scientific Liaison Representative.

This report gives a brief coverage of the program. Detailed presentations and discussions are given in existing publications and other publications that are in process. Many people participated in this program and they are listed in this report. Where appropriate, they are included as authors of the various publications.



STATEMENT OF THE PROBLEM

This research program was concerned with the structure and characteristics of heterogeneous detonation; specifically, sprays in a gaseous oxidizer. Relative to this aim, particular aspects of interest were:

1. Examine the structure of the heterogeneous wave by means of high speed photography, pressure measurements, and wave propagation rates.

2. Determine the wave propagation rates, pressure ratios, and critical initiation energies required for a number of variables; i.e. various equivalence ratios, a range of N_2/O_2 ratios, the vapor pressure of the fuel, and the influence of additives to the fuel.

3. Treat the heterogeneous detonation problem analytically in order to better assess the critical features and to enhance predictive capability.

SUMMARY OF THE RESULTS

A detailed discussion of the major research findings of this program is given in the various publications listed later on in this report. Accordingly, only a brief discussion will be presented here.

The experimental portion of the program was conducted in a long vertical detonation tube. An existing tube required rather major alterations. A new, longer section of the main tube was readied and assembled into the system so that a vertical tube 8.2 m in length and of 4.1 x 4.1 cm inner cross-section dimensions was available. Eleven pressure switches and two high frequency response pressure transducers were spaced along the tube so that wave arrival times (and hence velocity) and pressure-time histories could be obtained. A test section with windows was also available for photographic studies. A new droplet generating system was also developed which mounted on the top of the vertical tube and served to produce a number of drops, all of the same size, falling vertically. The generating system consisted of a liquid fuel reservoir, a capillary needle plate, and a vibrator. The fuel was pressurized and caused to flow through the needles. This flow was perturbed at the Rayleigh frequency so as to produce drops of 400 micrometers. One of four different needle plates (9, 13, 19, or 25 needles) could be used, dependent upon the total fuel flow desired. Initiation of detonation was achieved through use of a shock tube mounted near the top of the vertical tube and at a 15-degree angle to it. Detonation of a gaseous mixture ($2H_2 + O_2 + He$), separated from the main tube by a diaphragm, transmitted a blast wave downward into the vertical tube. The initiation energy was varied by controlling the pressure of the gaseous mixture before detonation. The fuel used in the experiments, for the most part, was decane, a very low vapor pressure fuel.

A great number of experiments were conducted wherein three different atmospheres(100% O_2; 40% O_2/60% N_2; and air at STP) and the four needle plates (therefore different equivalence ratios) were used. Detonation propagation rates, pressure histories, and the critical initiation energy were established for a number of these conditions. In general, the 100% O_2 and 40% O_2 atmospheres did not lead to significant differences in detonability; they were relatively easy to detonate. However, use of air as the oxidizer precluded the attainment of detonation.

The above experiments, for selected conditions, indicated some interesting differences in the blast wave initiation of detonation. At high initiation energies, E_o, detonation was achieved 100% of the time by direct decay of the strong wave into detonation. With some reduction in E_o, a range of E_o was found wherein detonation was achieved in only a fraction of the runs. With a further decrease in E_o, there was a range where detonation again occurred 100% of the time. In this range the initial wave had decayed to velocities well below Chapman-Jouguet but then a transition process occurred which led to detonation. As E_o was decreased still further, detonation occurred only a fraction of the time and, finally, for sufficiently low E_o, detonation never occurred.

Addition of normal propyl nitrate (NPN), a monopropellant with high vapor pressure, to the decane increased the sensitivity of the mixture. This sensitivity increased with increasing amounts of NPN; it led to detonation in air, to lower critical initiation energy, and to wider detonation limits for equivalence ratio.

In recognition of the fact that aerodynamic shattering of the drops behind the shock plays an important role in heterogeneous detonations, some holograms of this phenomena were taken. While the density of the microspray in the wake of the parent drop was too dense to penetrate optically, it was possible to identify microspray droplets on the fringe of the wake. These drops appeared to be monodisperse and about 10 micrometers in diameter. Some high speed streak photographs of heterogeneous detonation, which show the delayed ignition in the wake with resultant blast waves, were also taken.

Some earlier research had shown a marked difference in the blast wave initiation of detonation for decane as opposed to heptane. These two fuels are very similar in physical and chemical characteristics except that the former has very low vapor pressure and the latter has high vapor pressure. Accordingly, experiments were conducted using the same fuel, decane, and varying the vapor pressure by increasing the temperature. The highest temperature tested was 60 degrees C. As expected, the detonability increased with temperature (vapor pressure). The critical initiation energy decreased, detonation velocity increased, and the mixture limits broadened.

In the analytical portion of the program, a numerical code, based on the Flux Corrected Transport algorithm, was used to compute the developing structure of a spray detonation initiated using a strong blast wave. The results demonstrated the transition from strong blast wave structure to the structure characteristic of a steadily propagating spray detonation. A simplified model of the spray detonation structure based on the energy release from the microspray torn from the large spray droplets during the breakup process was also developed. This theory can be used in simplified theories of the initiation process.

In recognition of the fact that two-phase flow phenomena play an important role in the induction zone of two-phase detonations, the equations governing this flow were integrated numerically. The results of this analysis clearly show the increase in temperature and pressure immediately behind the shock, which are characteristic of two-phase flow.

The propagation velocity of spray detonation is significantly less than that computed for an equivalent gaseous fuel-oxidizer mixture. Losses to the wall of the detonation tube are insufficient to explain all of this difference; however, simple calculations using a previously developed model based on incomplete droplet burning gave results in good agreement with experiment.

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